Design, Development and Application of New, High-Performance Gear Steels

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Management Summary

QuesTek Innovations LLC is applying its *Materials by Design* computational design technology to develop a new class of high-strength, secondary hardening gear steels that are optimized for high-temperature, low-pressure (i.e., vacuum) carburization. The new alloys offer three different levels of case hardness (with the ability to "dial-in" hardness profiles, including exceptionally high case hardness), and their high core strength, toughness and other properties offer the potential to reduce drivetrain weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear Alloy 53. This new class of alloys utilizes an efficient nanoscale M_2C carbide strengthening dispersion; their key benefits include: high fatigue resistance (in contact, bending and scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of 900°F or higher (providing up to a 500°F increase in thermal stability relative to incumbent alloys); and core tensile strengths in excess of 225 ksi. Ferrium C61 is one alloy in this family and is currently used in transaxle ring and pinions for SCORE 1600 class off-road racing cars as well as process equipment applications. C61 is also being examined in an Army SBIR (Small Business Innovation Research) program as a potential replacement for 9310 in CH-47 Chinook helicopter main rotor mast applications, yielding a projected potential weight savings of 15–25%. Secondly, Ferrium C64 is being developed under a Navy STTR (Small Business Technology Transfer) program aimed at rotorcraft gear transmission applications in order to reduce weight, improve fatigue performance and improve high-temperature operating capability relative to the incumbent alloy Pyrowear Alloy 53. Lastly, Ferrium C69 can achieve a carburized surface hardness of HRC 67 (with a microstructure substantially free of primary carbides) and has exceptionally high contact fatigue resistance, which makes it a candidate for applications such as camshafts and bearings, as well as gear sets.

Introduction

Carburized steel gears are widely used for power transmission in rotorcraft, transportation vehicles, agricultural and off-road equipment, industrial rotating equipment and thousands of other applications. Commonly used alloys such as AISI 9310 (AMS 6265) and Pyrowear Alloy 53 ("X53") (AMS 6308; UNS K71040) have functional limitations that may not meet all of the performance requirements arising in next-generation equipment. Increasing demands to reduce energy consumption, material use and environmental impact are driving the need for dramatic improvements in gear steel manufacturing and performance. For example, the *Gear Industry Vision: A Vision of the Gear Industry in 2025* (published in 2004 by AGMA, ASME and other leading governmental, professional and commercial interests), identified strategic goals such as "Increase power density by 25% every five years (Ref. 1)." Or, as another example, the U.S. Navy estimates that a 20% increase in gear endurance could provide $17 million per year in cost savings to the Defense Logistics Agency alone (Ref. 2).

Past efforts to increase the power density, reliability or endurance performance of gears have included studies of hard tribological coatings; however, many potential coatings do not work well due to processing constraints or poor adhesion to the underlying alloy (Refs. 3–5). Powder alloy approaches have also been studied, but are often inadequate for fatigue-limited applications due to the higher fraction of oxide inclusions and porosity, which can act as fatigue initiation sites. Many improvements in the fatigue performance of commonly used alloys have been made using surface processing technology advancements such as superfinishing, shot peening, laser

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shock peening or cavitation peening. But these do not improve the intrinsic characteristics of the base alloys. This paper summarizes a first-principles-based, integrated computational materials design approach that is being used to create next-generation, high-performance base alloys with improved performance and reduced manufacturing complexity and variability.

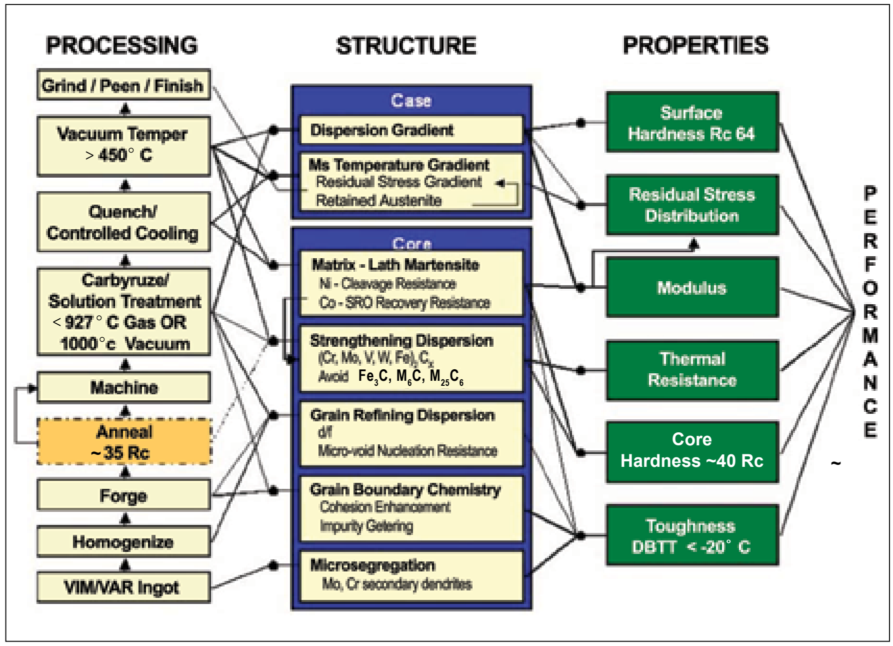

Figure 1—The "Design Chart" used by QuesTek to design the Ferrium C64 alloy. The hierarchical relationships between processing, structure, properties and performance are summarized graphically and serve as the template for alloy design.

Overview of Computational Materials Design Technology

New materials have historically been discovered either by chance or by intricate and costly cycles of trial and error, yielding a limited understanding of optimization and design. The limitations of the past approach are widely known, and numerous national studies over the past decade have consistently emphasized that traditional, empirical material development methods have not kept pace with modern, design-based product development efforts. One result is that a number of renowned materials companies have all but dropped their labor-intensive internal research and development programs due to their prohibitive cost, and have instead refocused their efforts on reducing costs to manufacture and process generic materials.

The use of powerful computational tools, property databases and intellectual expertise to computationally design and create new materials is a rapidly emerging, alternative approach. These techniques can be used to quickly and economically design and develop unique materials as integrated systems in order to deliver optimal performance requirements for a given application. The Steel Research Group (SRG) at Northwestern University of Evanston, IL pioneered this technology beginning in the mid-1980s. The strategic importance of computational materials design to the national mission was set forth in 2000 when the U.S. President's Office of Science and Technology identified computational design of materials as one of five critical technologies for the coming decade (Ref. 6).

Evanston, IL-based QuesTek is building on the SRG's initial efforts by using its proprietary *Materials by Design* technology to computationally design many new materials, including: iron-, copper-, aluminum-, nickel-, niobium- and titanium-based materials. Dr. Gregory B. Olson, the Wilson-Cook chaired professor in engineering design at Northwestern University's Department of Materials Science and Engineering, is QuesTek's chief science officer and a founder of the company. QuesTek was one of only a few commercial firms highlighted in 2008 by the U.S. National Research Council as examples of firms utilizing Integrated Computational Materials Engineering (ICME) for integrated manufacturing, materials and component design (Ref. 7).

The computational materials design approach considers material design goals and desired performance in the context of a material system. This approach integrates materials process-structure and structure-property models in a systems-based framework in order to meet specific, defined engineering needs, and to also address manufacturing processes and material qualification hurdles (including prediction of manufacturing variation). Like any other design effort, judicious decisions regarding key trade-offs among many competing requirements are often needed. Combinations of properties must be considered within specified process, cost, environmental and life-cycle constraints. Advanced computational modeling tools provide valuable scientific understanding in order to optimize such trade-offs in an efficient and knowledgeable manner, and typically provide enough fidelity to not only determine the favorability of one design solution over another, but to also search for design optima in previously unexplored terrain.

Some of SRG's and QuesTek's work has focused on computationally designing next-generation, high-performance gear steels in order to significantly improve performance properties such as strength, corrosion resistance, wear resistance and fatigue resistance while designing for robust, efficient and flexible processing paths. The new resulting alloys are in a class of QuesTek alloys termed Ferrium alloys.

Design and Overview of Ferrium Gear Steel Alloys

Ferrium C61, C64 and C69 are three new alloys being used or considered for power transmission applications. All of these alloys utilize an efficient nanoscale

continued

M_2C carbide strengthening dispersion within a Ni-Co lath martensitic matrix. Utilizing their suite of computational models, QuesTek designed these alloys considering the complex interplay of critical design factors including: martensitic matrix stability (M_s temperature); M_2C carbide thermodynamic stability and formation kinetics; matrix cleavage resistance; and embrittling phase thermodynamic stability.

The hierarchical relationships between processing, structure, properties, and performance are summarized by QuesTek in the form of a "Design Chart," which serves as the template for alloy design (Fig. 1). The performance of the alloy is embodied in the combination of properties outlined in the column on the right. The design process determines suitable microstructural concepts to meet these property goals, as indicated by the middle column. Available processing paths to access the microstructural objectives are quantified in the left column. The links between the subsystem blocks in the flow-block diagram represent process-structure and structure-property models required to quantitatively design an alloy to meet the desired material performance objectives.

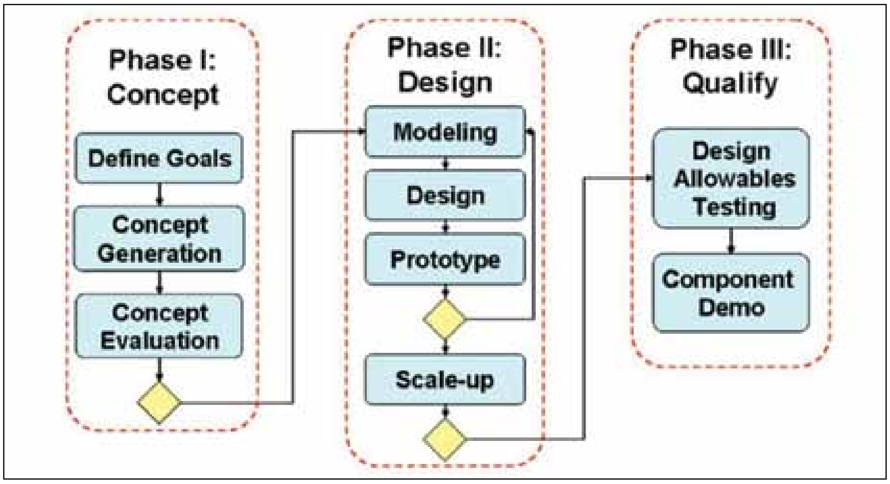

Figure 2—Overview of QuesTek's custom stage-gate process showing the development of a new material from identification of the customer-defined needs through qualification and component demonstration.

Alloy	YS (ksi)	UTS (ksi)	Core Hardness (HRC)	El (%)	RA %	Fracture Toughness (ksi√in)	Achievable Surface Hardness (HRC)	Tempering Temperature (°F)
AISI 9310	155	175	34-42	16	53	85	58-62	300
Pyrowear Alloy 53	140	170	36-44	16	67	115	59-63	400
Ferrium C61	225	240	48-50	16	70	130	60-62	900
Ferrium C64	199	229	48-50	18	75	85	62-64	925
Ferrium C69	195	235	48-50	19	65	40	65-67	925

Figure 3—Tabular comparison of core properties (typical).

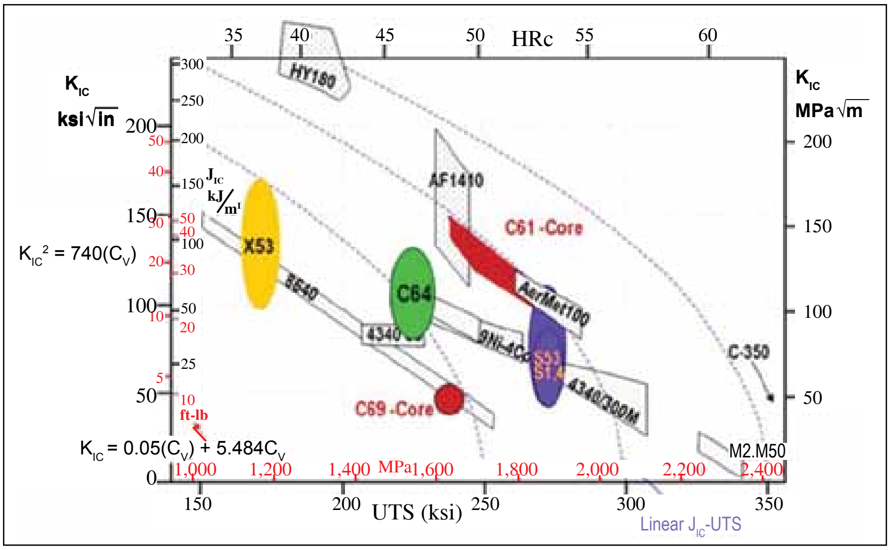

Figure 4—Graphical comparison of core properties and design targets.

As it has done in its other development programs (Ref. 8), QuesTek and its partners utilized its custom stage-gate process, as illustrated in Figure 2, to design and develop the Ferrium alloys in a rapid manner while minimizing development costs. The process begins by working with the key stakeholders, such as gear designers and manufacturers, to establish specific system property goals and processing constraints. Within these customer-defined objectives, QuesTek applied its computational models to explore viable microstructural concepts. With the most promising concept selected, the alloy design plan is reviewed for its viability prior to proceeding to the design phase.

QuesTek's *Materials by Design* process is iterative, with review meetings at critical decision points throughout the modeling, design and prototyping tasks. After completing the initial modeling and prototype designs, QuesTek procures sub-scale ingots to validate the proof-of-concept with material testing and microstructural characterization.

Having achieved the design goals with sub-scale material, QuesTek proceeds to full-scale commercial production. For example, QuesTek prototyped Ferrium C64 with one round each of sub-scale and intermediate-scale prototypes prior to the finalized commercial-scale production.

The objective of the final phase of QuesTek's alloy development process is to develop materials design allowables of the alloy and to manufacture full-scale components. These two tasks may be executed in parallel, depending upon the specific situation at the time. Multiple heats of the alloy may

be required for statistical development of materials design allowables. In the case of the gear steels, this includes rotating gear and rig testing to provide statistically validated fatigue design data. The majority of the work in the qualification phase of development is performed by (QuesTek) manufacturing partners and leading adopters of the material. QuesTek's design methodology yielded a number of attractive material properties for C61, C64 and C69 alloys. A tabular and graphical summary of key properties versus common, incumbent materials is shown in Figures 3 and 4.

These properties, and the material processing routes available with these materials, yield performance features such as the following:

Greater core strength. These alloys exhibit core steel tensile strengths (UTS) of 229 ksi or more, which is a + 35% increase versus conventional gear steels and allows significant reductions in part size and weight, particularly where structural components are integrated with gearing into single components.

Greater surface fatigue resistance. These alloys demonstrate high surface fatigue resistance, which leads to increased contact fatigue and bending fatigue performance. Generally speaking, increasing the surface hardness without creating embrittling features (such as interconnected primary carbides) increases surface fatigue resistance. Since surface fatigue resistance can often be a limiting factor in gear design, increased surface fatigue resistance can enable either smaller, lighter-power transmission units or higher power throughput in a given unit size.

High surface hardenability designed to use high-temperature, low-pressure (vacuum) carburization methods. These alloys were specifically designed to achieve high surface hardenability and to use high-temperature, low-pressure (vacuum) carburization and gas quenching processing methods, the combination of which can permit significant reductions in manufacturing costs and schedules due to:

- shorter processing times at higher carburizing temperatures
- elimination of the secondary hardening and oil quench process step, and the associated costs of custom press quench dies, liquid quenchants, rapid transfer mechanisms, hydraulic systems, etc.
- reduction of excess grinding labor, excess stock removal waste and part scrap waste; by reducing part quench distortion and avoiding the intergranular oxide (IGO) formation inherent in a pre-oxidation step, the slower gas quench process is far less severe and far more spatially uniform than a rapid liquid quench
- enhanced manufacturing flexibility and control, due to the ability to "dial in" the depth and profile of case carburization

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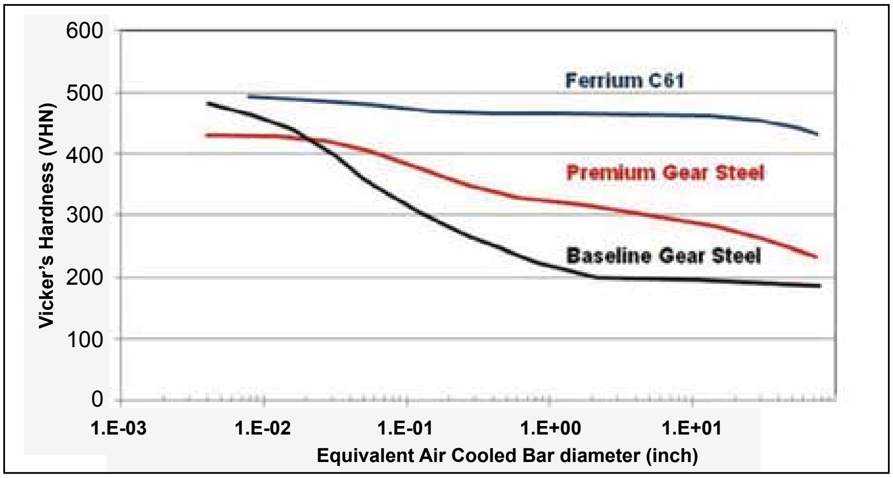

Figure 5—Hardenability comparison for center of an air-cooled bar between legacy baseline steel, current premium grade steel and Ferrium C61.

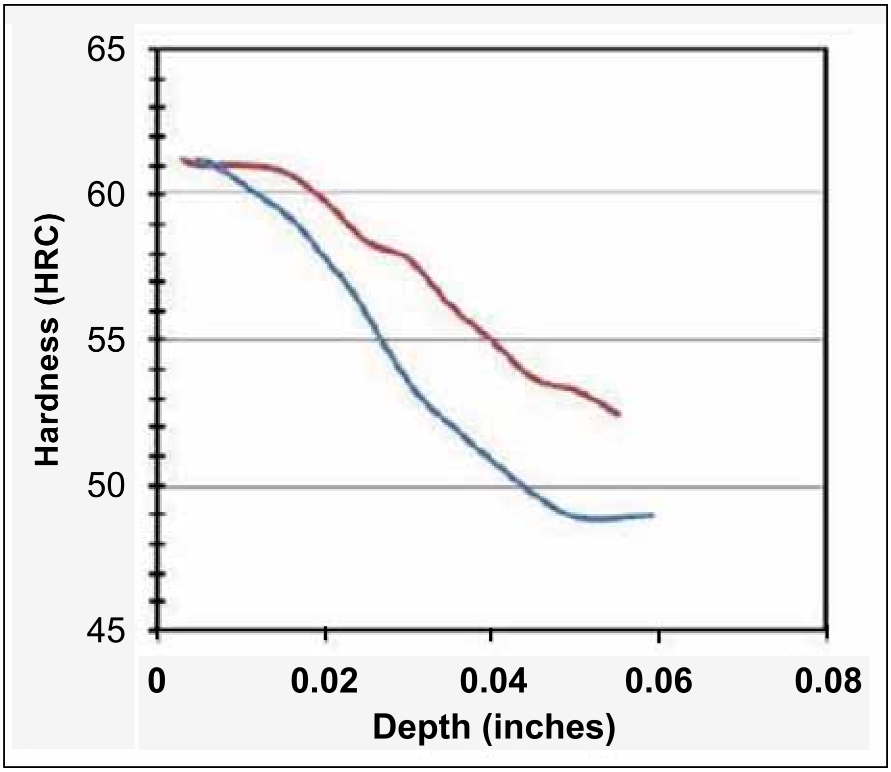

Figure 6—Two different hardness profiles developed in Ferrium C61 using two different carburization and heat treatments illustrate the ability to "dial in" the depth and carburization profile in Ferrium gear steel alloys, in order to allow for differing amounts of lapping or grinding stock removal.

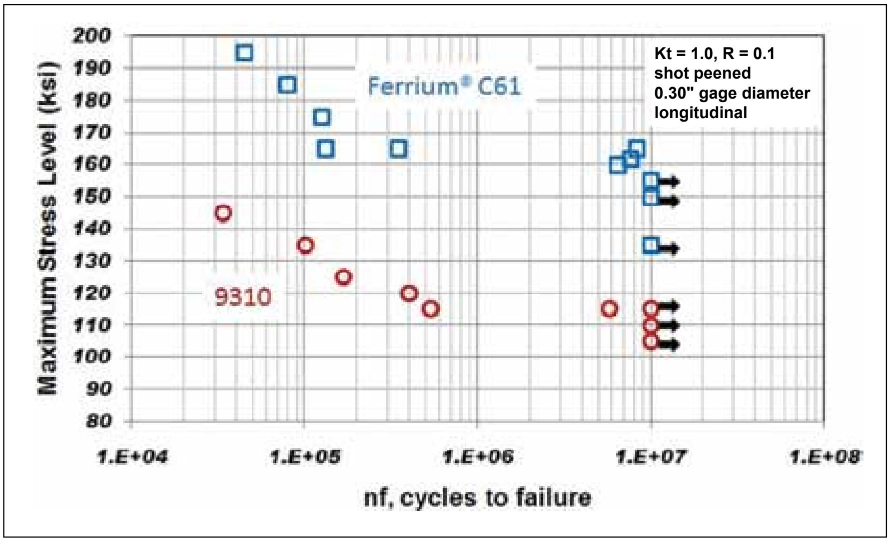

Figure 7—C61 exhibits improved axial fatigue performance relative to 9310, (smooth bar axial fatigue testing, shot peened specimens; arrows denote runouts) in this data developed under U.S. Army Contract #W911W6-09-C-0001.

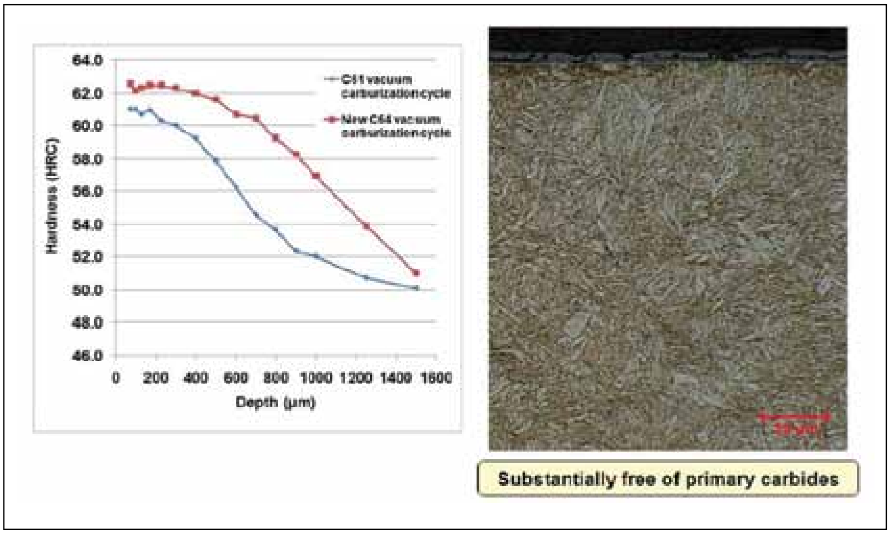

Figure 8—Comparison of C64 and C61 hardness profiles from typical carburization cycles (left), and photograph of C64 microstructure illustrating absence of primary carbides (right).

For example, the high hardenability of Ferrium C61 when compared to a conventional, baseline gear steel, as well as a premium gear steel, is illustrated in Figure 5.

Greater High-Temperature Survivability

These alloys exhibit increased thermal stability versus AISI 9310 or Pyrowear X53 because they were designed to be tempered at 900°F or 950°F, which is up to 500°F hotter than AISI 9310 or Pyrowear X53. Increased thermal stability is expected to result in a greater ability for a gearbox to survive "oil-out" or low-lubricant situations, and to endure other high-temperature operating conditions. Additional information about the properties and development status of each alloy is described separately below.

Ferrium C61. Ferrium C61 was designed to provide a carburized surface hardness of 60–62 Rockwell C Hardness (or HRC), which is similar to conventional gear steels such as X53 (59-64 HRC) and AISI 9310 (58-64 HRC), but delivers ultra-high core strength and excellent fracture toughness comparable to AerMet 100. C61 has surface-wear properties, toughness (~130 ksi√in), and case fatigue properties that are similar to those of current commercial alloys, but C61's typical core hardness of 49–50 HRC far exceeds X53's core hardness of 36–44 HRC. In addition to increasing the maximum allowable load, the increased core strength has been shown to increase fatigue strength. C61's good combination of strength and toughness can enable weight reductions in shafts and other integral structural components compared with alternative gear materials.

As summarized earlier, the ability of this class of alloys to use low-pressure (vacuum) carburization and gas quenching offers a number of benefits, including reduced part distortion during quenching (to reduce subsequent machining waste and scrap) as well as simpler part clean-up. The ability to "dial in" the depth and profile of carburization in this class of alloys is illustrated in Figure 6, which shows two different hardness profiles achieved in C61 using different carburization and heat treatment cycles.

This flexibility in creating hardness profile depths and profiles provides gear designers and manufacturers the opportunity to optimize the material for best performance. To achieve this variation, several boost cycles ranging from 20–120 seconds and diffuse cycles ranging in time from 15–45 minutes have been used to achieve targeted case depths of about 0.040" with the various profile shapes. Various carburizing cycles have been developed for C61 in order to develop different case depths and profile shapes. It is anticipated that SAE AMS 2759/7 (when issued) will provide specific thermal processing guidelines for C61. One independent review of low-pressure carburization process cycles, including for C61, is also available in the recent literature (Ref. 11).

Ferrium C61 has found considerable success in off-road racing, and in particular in the 1600 class of the SCORE off-road desert racing series. The rules for the 1600 class in the SCORE racing series require 1600 cm^3 engines and 091 Volkswagen transaxles, which were originally designed to accommodate 40–60 horsepower in street vehicles. When used in off-road racing, the modified engine power out-

put is double that of the stock engine, and the drivetrain experiences severe impact loads due to the rough terrain, which results in these transaxles being loaded far in excess of their design limits. Ring and pinion sets made from C61 have proven to be far more durable than those made of other gear steels. The C61 ring and pinion set was officially introduced in January 2005 at the SCORE Laughlin Desert Challenge, with over 40% of the cars adopting C61 sets by the end of the first season. C61 gear sets do not typically need to be replaced after each race, as is commonly necessary for sets manufactured from 8620. Ring and pinion sets made of C61 are typically replaced only once per racing season, whereas 9310 sets were often replaced after each race (which greatly increases the time and cost to prepare the car before each race). In general, ring and pinion gear sets manufactured from C61 are achieving at least 3–4 times greater lifetimes than the same sets manufactured from 9310, with some C61 ring and pinion sets lasting as long as two full racing seasons. C61 has also been applied in process machinery and other power transmission applications.

C61 can offer an attractive combination of properties for integral power shaft and gearing applications, where both the core strength and the fatigue strength of an alloy are critical. As an example, C61 is being evaluated for main rotor shaft applications on the Boeing-designed CH-47 Chinook helicopter in a U.S. Army Small Business Innovation Research (SBIR) program. Main rotor shafts, specifically those used on the CH-47, are among the largest, heaviest, and highly loaded single components on rotorcraft. With its improved core properties (Fig. 3), use of C61 in lieu of the currently used carburized 9310 may be able to reduce the weight of the main rotor shaft on the CH-47 by 15–25% without requiring significant changes in the production process of the component. C61 may also provide benefits in thermal resistance, ballistic performance, and stress-corrosion cracking resistance; i.e., a material upgrade may hold promise for both weight reduction and performance enhancement. Data developed under this SBIR program demonstrates the superior axial fatigue life performance of C61 versus 9310 (Fig. 7).

Ferrium C61 material is commercially available from a major commercial alloy producer operating under a license from QuesTek. QuesTek anticipates licensing additional producers in order to establish a robust, competitive market for C61. The composition of C61 is covered under U.S. Patent Number 6,176,946 B1. QuesTek also anticipates beginning the process of obtaining an SAE Aerospace Material Specification for C61.

Ferrium C64. QuesTek is currently developing Ferrium C64 under a U.S. Navy STTR program to achieve higher surface hardness than C61 while retaining superior core hardness, fracture toughness, high allowable operating temperature, and other manufacturing benefits. The platform sponsor is the V-22 Osprey and an ultimate improvement in rotorcraft transmission power density is sought relative to Pyrowear Alloy 53, the incumbent carburized gear steel. Ferrium C64 material is commercially available from a major commercial alloy producer, operating under a license from QuesTek.

The primary anticipated benefit of this STTR program is to demonstrate dramatic increases in main gearbox power densities within the Navy's rotorcraft fleet. New materials to increase power load and reliability without increasing the size of these components would have a significant impact. While C64 was designed and developed within this STTR program specifically for helicopter gears, it is expected to be applicable to other non-military, high-performance power transmission applications where weight, compactness, durability and high-temperature capability are valued.

This establishment of the design requirements and the development of the alloy was a collaborative effort among materials design engineers at QuesTek and the Navy; gear and drivetrain engineers from Bell Helicopter Textron Inc.; and gear testing experts from the Gear Research Institute (GRI) at The Pennsylvania State University.

Ferrium C64 has been produced at full industrial scale (multi-ton) in final product sizes of 4.5" OD and 6.5" OD. Vacuum carburized surface hardness profiles show a marked increase in surface hardness over C61 with a carburized surface microstructure that is substantially free of primary carbides

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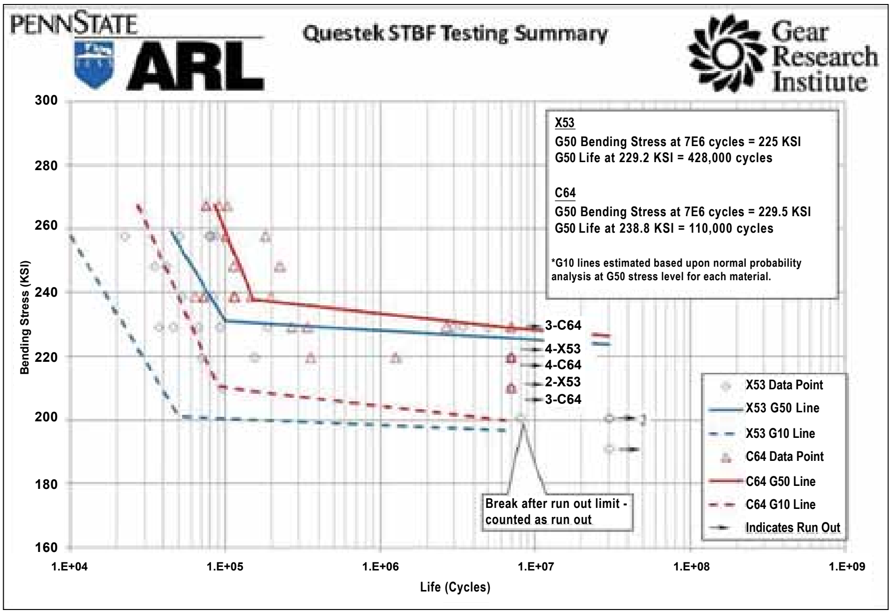

Figure 9—Results of single tooth bending fatigue (STBF) tests of C64 in comparison to X53.

(Fig. 8). Development of fatigue data is ongoing under the Navy STTR program, and single-tooth bending fatigue (STBF) results have been developed (Fig. 9). With fatigue performance comparable to that of X53, C64 is particularly attractive as a "drop-in" X53 replacement due to its high hardenability, ease of manufacturing and processing, and temperature resistance.

Rotating fatigue tests (contact fatigue, bending fatigue, scoring fatigue) are currently being planned for C64 in conjunction with Penn State. Other evaluations may include temperature resistance tests ("oil-out" testing) and full (planetary) gear rig testing.

The rapid development of Ferrium C64 illustrates the power and speed of using a computational material design approach to capitalize on specific product design needs as well as opportunities for product/material improvement. The material design goals and the Design Chart (i.e., Figure 1) were formulated in September 2005, under Office of Naval Research contract #N00014-05-M-0250 (issued August 9, 2005). In less than one year, the basic alloy composition and processing route were computationally designed, and the alloy was produced at a 30 lb. prototype size. In less than two years, the material was successfully produced at full industrial scale (i.e., 10,000 lbs.).

Ferrium C69. Ferrium C69 is a high case hardness variant that can be tempered to achieve a case hardness of up to 67 HRC, and yet be substantially free of primary carbides in the microstructure. These surface properties can allow higher power density or greater surface wear resistance than conventional commercial carburized gear steels, with potential uses such as select gearbox applications, camshafts and bearing surfaces.

High case hardness is correlated with high contact fatigue resistance and bending fatigue resistance. The NASA Glenn Research Center performed contact fatigue testing on C69 using its spur gear fatigue rigs, the same rigs used for identical tests on current commercially available gear steels. A set of C69 gears that was tested represent the best-performing set of "standard-ground finished" gears tested to date on the NASA Glenn Research Center's gear test apparatus. C69 demonstrated almost a threefold increase in fatigue cycles at the L50 life and almost a twofold increase at the L10 life over Pyrowear X53. Microhardness traces were taken from the flank, mid-flank and root to verify consistent properties. In each instance the case hardness was 65 to 66 Rc, which is well above the 60—62 Rc observed in 9310 and Pyrowear X53. Figure 10 shows data generated by NASA Glenn on both C69 and Pyrowear X53. Additional data from these tests has been published elsewhere (Ref. 12). A high hardness case material such as C69, C64 or C61 can maintain increased residual compressive stress upon shot peening or laser shock peening, which has additional benefits for fatigue resistance. QuesTek fully expects an additional, sizeable benefit in contact fatigue performance from shot peening of C69, C64 or C61. However, for a fair comparison and for consistency with previous NASA tests, none of the C69 specimens tested for Figure 10 were shot peened.

Ferrium C69 is currently available in prototype quantities directly from QuesTek. QuesTek expects to license the production of C69 to commercial alloy producers in response to market demand. The composition of C69 is covered under U.S. Patent Number 6,176,946 B1.

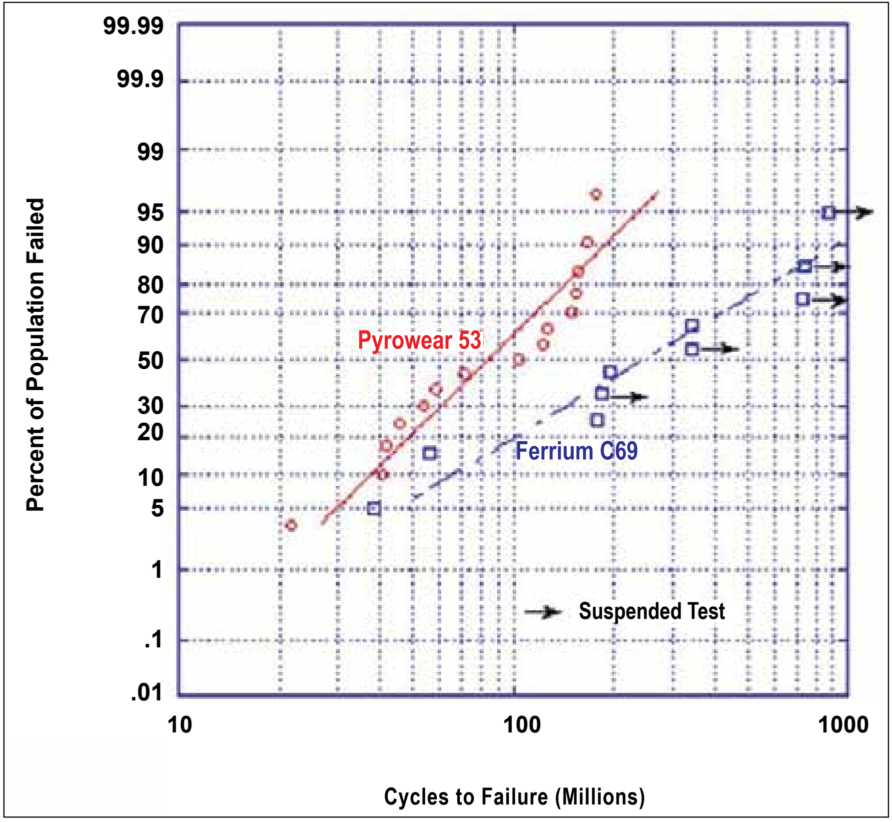

Figure 10—Surface contact fatigue probability plot for Ferrium C69 and Pyrowear X53 generated by NASA Glenn Research Center.

Conclusions

Integrated computational design methods, models and property databases continue to rapidly advance and improve, yielding rich design insights into controlling key property performance issues such as strength, thermal stability, fatigue resistance, ductility and corrosion resistance. These cutting-edge tools apply to the design of both materials as well as material processing and manufacturing, and can quickly and efficiently find optimal solutions, identify failures, and search optimums in previously unexplored concept spaces.

The design of Ferrium C61, C64

and C69 alloys provides a case study illustration of computational material design tools and principles applied to iron-based material microstructures. This new class of gear steel alloys utilizes an efficient M_2C precipitate strengthening dispersion, and offers a number of key benefits in manufacturing, as well as performance, over incumbent alloys such as: reduced manufacturing complexity and variability by using low-distortion gas quenching and by eliminating liquid quenchant systems and steps; reduced gear set weight and increased power density due to increased surface fatigue resistance; improved "oil-out" survivability (due to a 500°F + increase in thermal stability); and increased core material properties. In summary, the computational design process has yielded three interesting, highly processable alloys that appear to offer significant advantages over several traditional material alternatives for power transmission applications.

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